

Satellite Flyby Opportunities for the Multi-Outer-Planet Missions

P. A. Penzo

Mission Analysis Division

In the proposed missions to the outer planets, observations of their natural satellites will be of considerable scientific interest. In this study, the satellite encounter opportunities are generated for two multiple-flyby missions which include all five of the major planets. Many favorable encounter opportunities have been found for the large satellites of Jupiter, and some for Titan and Iapetus of Saturn. The opportunities for satellites of Uranus are least favorable. Opportunities also exist for multiple-satellite encounters on the same mission and examples are shown. Finally, for Jupiter, some arrival dates exist where very close flybys of certain satellites are possible. These opportunities, added to the multiple-planet missions, will enhance their scientific return significantly.

Introduction

During the late 1970s, the favorable configuration of the outer planets leads to unique opportunities to fly by several of these giant planets with a single spacecraft. Thus, with a bit more energy than is required to get to Jupiter, for example, it will be possible for the spacecraft to acquire a gravity-assisted energy increase at Jupiter sufficient to go on to Saturn and then to Pluto. Several combinations of such multiple-planet missions have been studied in detail (e.g., Reference 1) where Jupiter is the first planet. Two such combinations have received considerable attention recently (Reference 2) and are seriously being considered as part of NASA's program to explore the outer planets. These are the Jupiter to Saturn to Pluto (JSP) combination, which has favorable launch periods in 1976, 1977, and 1978; and the Jupiter to Uranus to Neptune (JUN) combination with favorable launch periods in 1978, 1979, and 1980. This study will concentrate on satellite encounter opportunities for two of the missions, i.e., JSP 77 and JUN 79.

Studies of these multiple-planet missions date back to 1966 (Reference 3); however, very little attention was given to the possibilities of

encountering the planets' satellites during these missions. Recently, however, scientific interest in the satellites has increased. Typical questions which may be asked concern their figures, possible atmospheres, magnetic fields, densities, and surface properties. Close encounters with the satellites may resolve some of these questions and, some scientists believe, lead to a better understanding of the origin and evolution of the solar system. This study shows that very near encounters with certain satellites are possible during multiple-planet missions and, if some sacrifice is made in approach distances, multiple-satellite encounters are also possible.

Flyby Characteristics

Due to the increased interest in the satellites, a systematic study was begun at JPL within the past year to determine possible satellite encounter opportunities during the JSP and JUN missions. Such satellite encounters require that two conditions be satisfied. The first requirement is that the

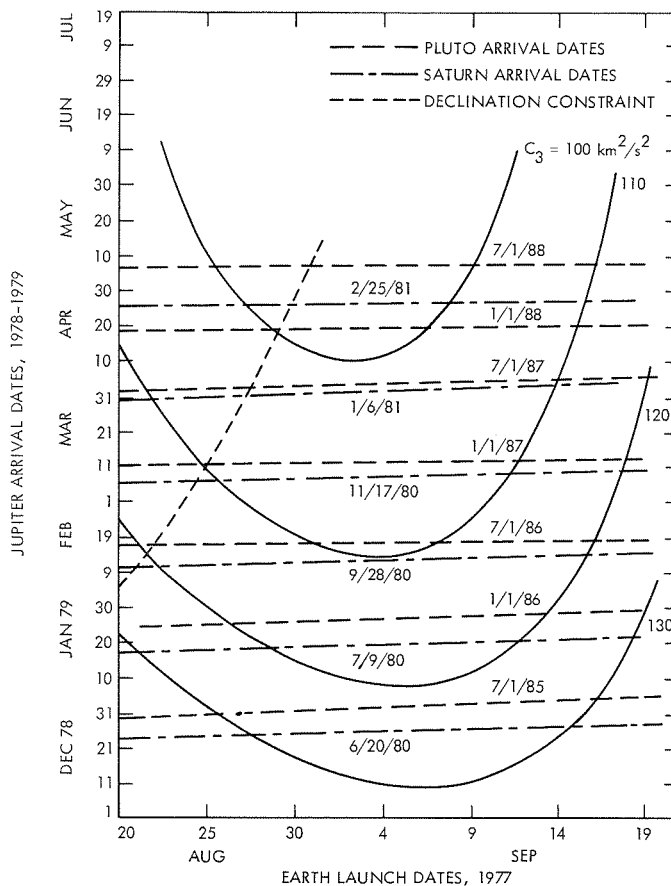


Figure 1. Launch and arrival times for the JSP 77 mission

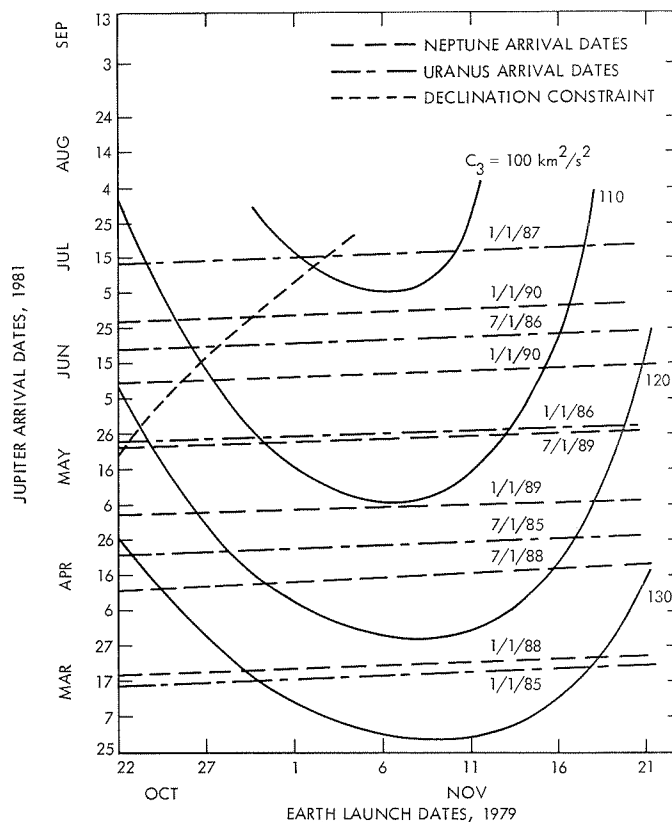


Figure 2. Launch and arrival times for the JUN 79 mission

flyby trajectory comes close to the orbit of the satellite of interest. This makes an encounter at least geometrically feasible, and will depend upon the flyby trajectory path relative to the satellite orbit. The second is that the satellite and the spacecraft be on their respective orbits at positions where the distance between the orbits is nearly minimum. Achieving this condition is primarily a matter of timing the spacecraft arrival at the planet.

The flyby characteristics,¹ in turn, are dependent on the particular planetary mission. For example, for a JSP mission, choosing an Earth launch date and Jupiter arrival date will completely specify the trajectory, except for the flyby geometry at the final planet. Elements specified include the launch energy, the intermediate planet flyby characteristics, and the arrival times at Saturn and Pluto. Figures 1 and 2, for example, present Jupiter arrival date versus Earth launch date for the JSP 77 and

¹The data presented here has been generated with conic programs which have not considered oblateness or third body effects. The accuracy of these programs is quite sufficient for the preliminary analysis presented here.

JUN 79 missions, respectively. Plotted² are lines of constant Earth launch C_3 , and the outer planets' arrival times. The launch asymptote declination line of ± 0.497 rad (± 28.5 deg),³ which may limit the length of the launch window, is also shown.

Several characteristics may be noted in these figures. The first is that the flight times to the planets will increase with decreasing C_3 . These flight times range from 450 to 600 days for Jupiter, 2.8 to 3.5 yr for Saturn, and 5.0 to 7.0 yr for Uranus. The flight times to the final planets, Pluto and Neptune, can vary from 7.5 to 11 yr. In addition, if the arrival date at a given planet is held fixed for a given launch period, perhaps to take advantage of a close satellite encounter which may occur on that date, the flight times to the remaining planets do not change appreciably (the actual changes may be read off these curves). The Earth launch C_3 ,

²The value of C_3 (km^2/s^2) is twice the energy per unit mass of the spacecraft after injection from Earth parking orbit. It is also equal to the square of the spacecraft hyperbolic excess velocity, V_∞ .

³Where applicable, the International System of Units is stated first, followed by the customary units in parentheses. In each case, the value in parentheses represents the measured or calculated unit.

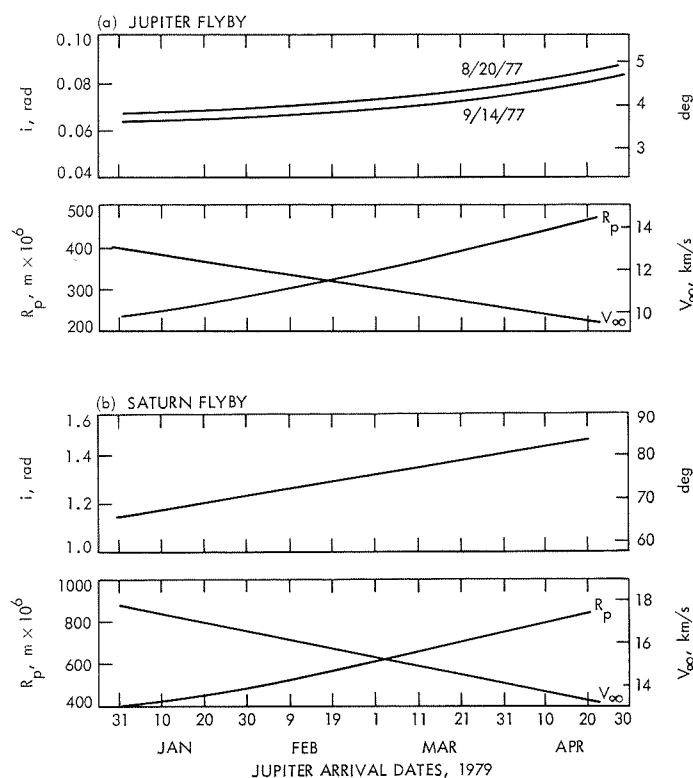


Figure 3. Hyperbolic parameters for the JSP 77 mission

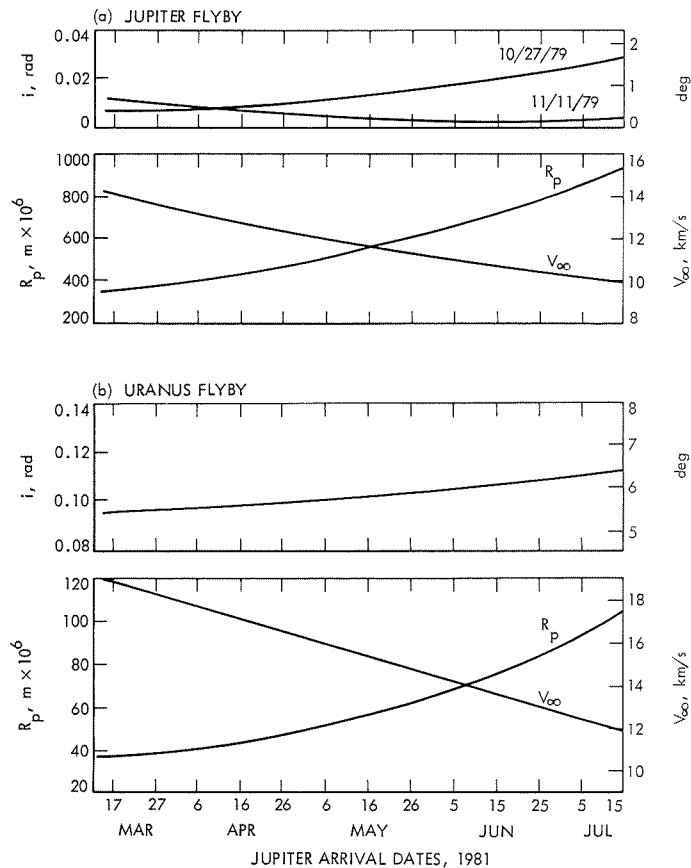


Figure 4. Hyperbolic parameters for the JUN 79 mission

however, will change, being a maximum at the beginning and end of the launch period and having a minimum near the center.

Figures 3 and 4 present some flyby parameters for the JSP 77 and JUN 79 missions, respectively, as a function of the Jupiter arrival date. These data are nearly independent of the launch date, except for slight variations in inclinations (i) at Jupiter. (All inclinations are relative to Earth ecliptic.) At Jupiter, the values and variations in the inclination are small. As discussed below, this characteristic is favorable relative to close encounters with the satellites of Jupiter. The high inclination of the Saturn flyby is due to the requirement that the spacecraft go on to Pluto, which is considerably out of the ecliptic plane at the time of Pluto arrival. Included in these figures are the radial distance of the flyby periapsis (R_p), given in kilometers, and the hyperbolic excess velocity at the planet. For flyby missions, this last parameter does not play a significant role in the planet and satellite encounters; however, for orbital missions the orbit insertion fuel requirements will have a strong dependence on this

parameter. For satellite encounters, the radial distance is important since it indicates how close to the satellite orbit the flyby trajectory may come.

Satellite Encounter Opportunities

Determining the characteristics of the flyby trajectories for the set of Jupiter arrival dates of interest, such as presented in Figures 3 and 4, is one necessary requirement for finding satellite encounter opportunities. In addition, it is necessary to know the characteristics of the satellite orbits themselves and, in fact, to know their positions as a function of time (their ephemerides). At present, for this and similar studies, JPL has implemented some long existing theories concerning the motions of the satellites of the outer planets. These ephemerides are sufficiently accurate for preliminary analyses. Anticipation of the need for greater accuracy is presently leading to increased activity at JPL and elsewhere to develop improved ephemerides for the satellites. Although the existing ephemerides were used to generate the encounter data presented in this study, it is useful to list here some of the gross characteristics of the satellite orbits.

Table 1 presents some satellite orbital data for Jupiter, Saturn, and Uranus. For Jupiter only the larger (Galilean) satellites are listed. For Saturn, two of the larger satellites are given, and these will be discussed later with regard to encounter opportunities. The five satellites of Uranus form an extremely regular system and the characteristics of all of them are presented. Considerably more information may be found in References 4 and 5.

Table 1. Satellite orbital data (The Ecliptic Coordinate System)

Satellite	Semi-major axis, km	Eccentricity	Inclination, deg	Ascending node, deg	Period, days
Jupiter					
Io	422,000	0.0	2.18	338	1.77
Europa	671,400	0.0003	2.22	350	3.55
Ganymede	1,071,000	0.0015	2.02	341	7.15
Callisto	1,884,000	0.0075	2.01	333	16.69
Saturn					
Titan	1,222,600	0.029	27.74	169	15.95
Iapetus	3,562,900	0.104	17.59	140	79.33
Uranus					
Miranda	129,800	0.0	98.0	166.4	1.41
Ariel	190,900	0.0028	98.0	166.4	2.52
Umbriel	266,000	0.0035	98.0	166.4	4.14
Titania	436,000	0.0024	98.0	166.4	8.71
Oberon	583,400	0.0007	98.0	166.4	13.46

Jupiter

Analyzing the characteristics of the flyby trajectories to the planets, and the satellite characteristics presented in Table 1, it has become evident that conditions for satellite encounter are much more favorable at Jupiter than at Saturn and Uranus. (Pluto has no known satellites, and the Satellites of Neptune may be targeted to since it is the last planet of the JUN mission.) Figure 5 presents the sets of flyby trajectories for the JSP 77 and JUN 79 missions and indicates that the flyby trajectories will lie very close to the plane of Jupiter's equator and hence to the plane of the satellite orbits. The earlier arrival date has been chosen on the basis that the total mission time is about 8 yr. The later arrival date assumes a total mission time of no more than 10 yr. The view in Figure 5 is from the ecliptic north pole. The inclinations of the flybys are all less than 0.1 rad (6 deg) to Jupiter's equator. Another favorable aspect of these trajectories is that their periapsides lie within the orbits of many of the satellites. Thus, the first condition for favorable satellite encounters is satisfied. Also, since the periods of these satellites are short (about 16 days for Callisto), compared with the range of possible arrival dates (about 3 months), there exist many Jupiter flyby times such that encounter with any given satellite is possible.

Based on the simplifying assumptions that the flyby trajectories are in the plane of the satellite orbits and that these orbits are circular (all

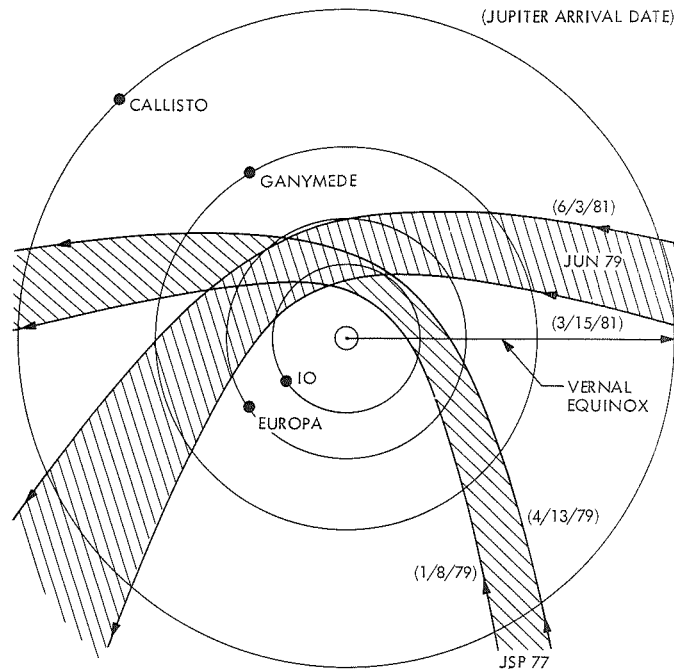


Figure 5. Sets of flyby trajectories for the JSP 77 and JUN 79 missions

eccentricities are less than 0.01), it is possible to generate satellite encounter times to an accuracy of about 0.1 day. (Actually, what is found is the Jupiter flyby time of closest approach which will produce an encounter with a given satellite.) This was done for the range of Jupiter arrival dates of interest. In determining the encounter times, the variation of the flyby altitude, energy, and orientation with the arrival date is taken into account. With these approximations as first guesses, it is a simple matter to calculate the exact encounter time and encounter characteristics with computer programs in which no simplifying assumptions are made.

Once these approximate single-satellite encounter opportunities have been generated, it is straightforward to find multiple-satellite encounters. Specifically, the data for single-satellite encounters consist of a list (for each satellite) of flyby periapsis times for which encounter with that satellite will occur. This list contains two sets, the first comprising those times for which encounter will occur prior to periapsis passage, and the second those times for which encounter will occur after periapsis passage. For multiple-satellite encounters, it is only necessary to scan the lists for all the satellites to find when the times are nearly coincident. For example, it may be found that a flyby periapsis passage on February 3.4, 1979, will result in an encounter with Europa prior to periapsis passage, whereas a periapsis passage on February 3.5, 1979, will result in an encounter with Io after periapsis passage. Thus, by compromising the

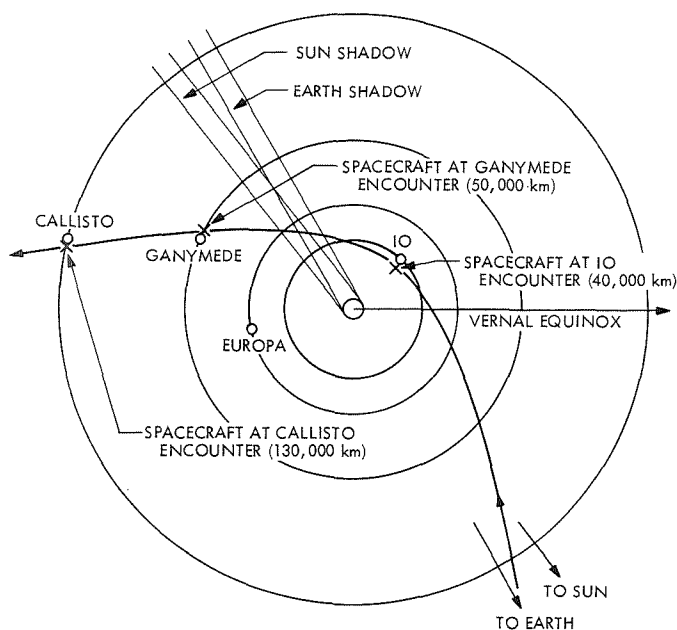


Figure 6. Possible Jupiter flyby with multiple-satellite encounters

periapsis time and targeting for a periapsis passage of February 3.45, 1979, it is possible to encounter both satellites, although some sacrifice in the closest approach distance to the two satellites will have to be made. Of course, the scan may (and does for JSP 76, as discussed in Reference 2) yield an opportunity to encounter all four of the Galilean satellites.

For the JSP 77 mission, several favorable multiple-satellite encounters exist for Io, Ganymede, and Callisto. The most favorable is shown in Figure 6, where the flyby periapsis time is March 5.3, 1979 GMT. For this case, the flyby periapsis is inside, but close to, Io's orbit, and encounter with Io (at a distance of about 40,000 km) occurs just prior to periapsis passage. Encounters with Ganymede and Callisto occur after periapsis passage with closest approach distances of about 50,000 and 130,000 km, respectively. Lighting conditions for viewing the three satellites is favorable.

Saturn

The method of analysis to generate the satellite possibilities and times that were used on Jupiter cannot be directly applied to Saturn. The reason is that the flyby trajectories are highly inclined to the ecliptic plane; about 1.3 rad (75 deg) for the JSP 77 mission as may be seen in Figure 3. On the other hand, most of Saturn's satellites are very close to the plane of the rings, which is inclined about 0.49 rad (28 deg) to the ecliptic. Thus, the flyby trajectories will be highly inclined to the satellite orbits. The first condition, then, that the flyby trajectory comes close to the satellite orbit, is less likely to be satisfied than for Jupiter, where the flyby trajectory and the satellite orbits are nearly coplanar.

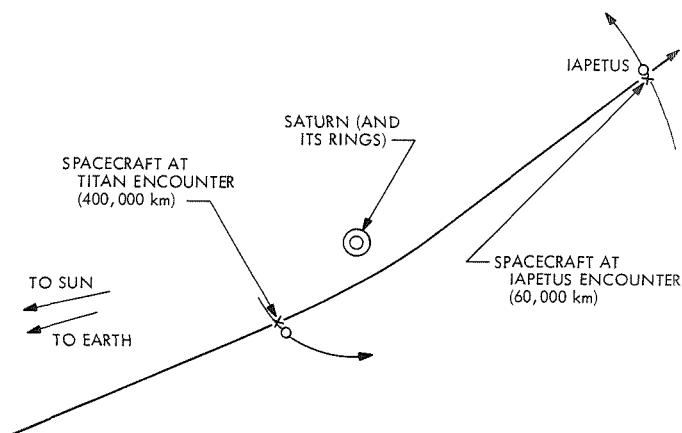


Figure 7. Possible Saturn flyby with multiple-satellite encounters

A preliminary analysis has been performed for the JSP 77 mission considering the possibilities of encountering the two larger satellites of Saturn, Titan, and Iapetus. Considering the out-of-plane condition, the possibilities are good. For Titan, the closest approach distance is about 400,000 km, and for Iapetus, about 60,000 km. Further, scanning the encounter times for Saturn arrivals ranging over a 6-mo period, a multiple encounter for Titan and Iapetus was found, where the closest approach distances are close to the values given above. The encounter opportunity is presented in Figure 7, as viewed from Saturn's north pole, where the time of periapsis passage is November 13.8, 1980 GMT. Because of the high inclination, there is no occultation of the spacecraft with Saturn as seen from Earth. This opportunity is rare because of the long period (79.3 days) for Iapetus.

Considering that Saturn has 10 known satellites, 7 of which have estimated radii, much of the analysis of encounters with these satellites lies ahead.

Uranus

For Uranus, which is considered in the JUN 79 mission, analysis of the flyby trajectory indicates that its plane is practically normal to the plane of the satellite orbits (all five of which lie in the plane of Uranus' equator and have near-zero eccentricity). In this extreme situation, a good approximation to the closest possible approach distance is simply the difference between the periapsis distance of the flyby trajectory and the semi-major axis of the satellite orbit. Referring to Figure 4, it is seen that the flyby periapsis distance is always less than the semi-major axis of Miranda (see Table 1), the innermost satellite of Uranus. Since the flyby altitude distance increases with flight time, the more favorable encounters will occur for the longer flight times (assuming that the time of periapsis is correctly chosen). A favorable aspect of the Uranus satellite encounter problem is the fact that the inner three satellites have short orbital periods (less than 5 days) allowing greater flexibility in timing the encounters, and possibly the performance of a midcourse maneuver to improve the encounter time.

Summary

The existence of favorable satellite encounter opportunities is most strongly dependent upon the geometric relationship between the flyby trajectory and the orbit of the satellite considered. For the JSP 77 and JUN 79 missions, this relationship at Jupiter is favorable. Thus, many encounter possibilities with the Jupiter satellites exist. For Saturn, the opportunities are less favorable, and for Uranus, they are quite unfavorable.

For Jupiter, with the approximate assumptions that the sets of flyby trajectories (Figure 5) are in the plane of the satellite orbits, and that

these orbits are circular, it has been possible to exhaustively determine the satellite encounter times. Essentially, these encounter times will occur twice during each revolution of the satellite, e.g., twice every 1.77 days for Io. Multiple-satellite opportunities are obtained by merely scanning the results and determining if there are several favorable encounters for the same flyby periapsis arrival time at Jupiter. Once these opportunities are found, a detailed analysis, utilizing the precise flyby trajectory and ephemerides of the satellite orbits, may be performed such as was done for the example given in Figure 6.

The encounter distance given in Figure 6 includes an out-of-plane component and, it is clear, that since the flyby trajectory characteristics change with Jupiter arrival date, this out-of-plane miss will also change. Analyzing the geometry more closely, it has become evident that this minimum distance can become quite small for certain satellites. This occurs when the flyby trajectory passes through the satellite orbit plane at the same time that it encounters the satellite. For JSP 77 this can occur for Ganymede before periapsis passage, and for Io and Europa after periapsis passage. For JUN 79, a near-zero encounter distance can occur for Io and Europa after periapsis passage. Determination of these closest approach times and the precise distance of these approaches has not been determined as yet; however, these times may offer opportunities to study a single satellite very closely, including possible occultations with Earth.

In summary, even with the trajectory restrictions which the multiple-planet missions impose, there exist possibilities to increase the scientific return and make these missions even more attractive by including close flybys with satellites.

References

1. Wallace, R. A., "Missions to the Outer Planets," in *Supporting Research and Advanced Development*, Space Programs Summary 37-54, Vol. III, pp. 35-36. Jet Propulsion Laboratory, Pasadena, Calif., Dec. 31, 1968.
2. Bourke, R. D., Friedman, L. D., Penzo, P. A., and Stavro, W., "Design of Grand Tour Missions," AIAA Paper 71-187, presented at the AIAA 9th Aerospace Sciences Meeting, New York, N. Y., Jan. 25-27, 1971.
3. Flandro, G. A., "Fast Reconnaissance Missions to the Outer Solar System Utilizing Energy Derived from the Gravitational Field of Jupiter," *Astronaut. Acta*, Vol. 12, No. 4, 1966.

References (contd)

4. Melbourne, W. G., Mulholland, J. D., Sjogren, W. L., and Sturms, F. M., Jr., *Constants and Related Information for Astrodynamic Calculations*, 1968, Technical Report 32-1306. Jet Propulsion Laboratory, Pasadena, Calif., July 15, 1968.
5. Newburn, R. L., Jr., *A Brief Survey of the Major Planets: Jupiter, Saturn, Uranus, and Neptune*, Technical Memorandum 33-424. Jet Propulsion Laboratory, Pasadena, Calif., Apr. 1, 1969.